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(3) DESIGN AND OPERATION OF THE X-15 HYPERSONIC RESEARCH AIRPLANE

by

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DESIGN AND OPERATION OF THE X-15 HYPERSONIC RESEARCH AIRPLANE

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G.R.Mellinger

This Report was presented at the Flight Mechanics Panel held from 3-5th October, 1960, in Istanbul, Turkey

SUMMARY

In 1952 the N.A.C.A. initiated a series of studies connected with space flight problems - an extension of work previously done on rocket research airplanes such as the X-1 and X-2. In 1954 NASA completed these studies and produced a proposal to the Air Force and Navy, for a hypersonic research airplane, the X-15. This Report describes the design and operation of this airplane.

SOMMAIRE

En 1952 la N.A.C.A. lança une série d'études portant sur les problèmes du vol spatial, et constituant une extension des travaux antérieurement effectués sur les avions fusées de recherche, par exemple, le X-1 et le X-2. En 1954 la N.A.S.A. ayant mené à fin ces études, soumit à l'approbation de l'Armée de l'Air et de la Marine Américaines un projet d'avion de recherche hypersonique. Cette communication a pour but d'exposer la conception et l'exploitation de cet avion.

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DESIGN AND OPERATION OF THE X-15 HYPERSONIC RESEARCH AIRPLANE

G.R.Millinger*

1. INTRODUCTION

In April of 1952 the N.A.C.A., since redesignated the National Aeronautics and Space Adminstration (N.A.S.A.), initiated studies for space flight problems. This was a logical extension of the work previously done on rocket research airplanes such as the X-1 and X-2 (Fig. 1).

In 1954, NASA completed its studies and presented the X-15 proposal to the Air Force and Navy. The proposal called for a boost glider vehicle as the stepping stone to space. This type of vehicle is boosted to high enough speeds so that the centrifugal force generated by following the earth's curvature supports a significant portion of the weight. It normally flies within the atmosphere, hence the name, glider; however, it can also be jumped out of the atmosphere to produce reasonably long periods of weightlessness characteristic of space travel.

In December 1955, North American was given the go-head to produce 3 vehicles, in accordance with its design proposal (Fig. 2), and in September 1959 the first powered flight was accomplished at Edwards Air Force Base.

2. DESCRIPTION OF VEHICLE

The N.A.S.A. specified certain design requirements for the airplane, to provide a manned research vehicle that would be capable of exploring the problems of hypersonic speed and space flight (Fig. 3). These were:

Maximum velocity, 6600 ft/sec

Capability of attaining at least 250,000 ft

Representative primary structure should be capable of withstanding a temperature of 1200^{o}F

Portions of representative structure should be able to achieve heating rates of 30 BTU/sq ft/sec.

These extremely severe design requirements dictated the need for a new liquid fuel rocket engine in the neighborhood of 60,000 lb of thrust. Weight is extremely important to the X-15, because of the ballistic trajectory flight path. To achieve minimum weight, many simplified systems were designed, and the normal landing gear was replaced by simple skids.

The high structural temperature and heating rates were obtained by re-entering the atmosphere at extremely high speeds obtained from ballistic trajectories above the atmos-

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phere. Atmospheric re-entry experience with manned aircraft and a period of weightlessness sufficient to extend our knowledge of its effect on human beings, would now be possible.

To determine the design conditions for the airplane, a maximum altitude mission profile (Fig. 4) and a maximum speed profile were chosen. For the altitude mission, a Mach number over 6 is reached at burn-out, and the vehicle coasts to the altitude of 250,000 ft. This mission results in an appreciable testing period at a combination of extreme altitude and Mach number. About 80 seconds after launch, the vehicle reaches Mach 6 and holds the speed for almost 200 seconds. The time of weightlessness is approximately 2.5 minutes.

For the maximum speed design mission (Fig. 5), the altitude is reduced to about 130,000 ft, and the required speed of 6600 ft/sec is realized. The structure was designed, therefore, to a dynamic pressure of 2500 lb/in^2, a load factor of 7.33 g, and approximately 1200°F maximum temperature.

To provide the thrust for the X-15, the U.S. Air Force contracted with Reaction Motors to develop a new turbo-rocket engine, designated as XLR99 (Fig. 6). Propellants are liquid oxygen and anhydrous ammonia supplied from gas-pressurized tanks. The engine is of variable-thrust design capable of operating over the range of 50 to 100% of full thrust. The gas generator decomposes a monopropellant fuel, 90% hydrogen peroxide, to provide a high-pressure gas mixture for driving the turbopump, which in turn drives the two centrifugal pumps that supply the propellants to the engine. The propellants then enter a first-stage igniter where the oxygen and ammonia are mixed and then ignited by three spark plugs. Liquid oxygen and ammonia also are routed to the second-stage igniter. Pressure switches in the first- and second-stage igniters are sequenced so that the propellants do not enter the main thrust chamber unless the first- and second-stage igniters build up the necessary pressure. The thrust chamber is an assembly of small, welded, wire-wound tubes preformed as segments of the chamber. Before injection into the thrust chamber, the ammonia passes through these tubes to cool the chamber. Several electrical circuits are provided that automatically shut the engine down, in the event of such malfunctions as overspeed or excessive vibration. A full-rated thrust of 57,000 lb is obtained at a maximum propellant flow rate of about 210 lb/sec. Because of the high thrust of the engine, the noise levels surrounding the vehicle are severe (Fig. 7). A maximum of 163 db is noted 25 ft behind the airplane. It was necessary to design the vehicle structure to withstand these high sound pressure levels, such as the 156 db at the horizontal stablizer position.

With the selection of the engine, an airplane layout was determined that would attain the desired performance (Fig. 8). A 5% thick wing, of modified hexagonal airfoil section, with a rounded leading edge and a blunt trailing edge, an aspect ratio of 2.5, and a 25-degree sweep angle was chosen. The fuselage is composed of the pilot's compartment, fuel and oxidizer tanks, and the engine compartment. All control cables, electrical leads and hydraulic lines, and other plumbing are routed in tunnels on the outside of the circular fuselage section.

With a propellant weight of 18,300 lb, the launching weight became 31,275 lb. The length of the vehicle is roughly twice the span of the wing.

Pitch control is obtained through the symmetrical deflection of both horizontal stablizers, and roll control is obtained by differential motion of the same stablizer surfaces. We call this, therefore, a 'rolling tail'. The horizontal surfaces are 5% thick, of the same airfoil section as the wing, and possess a cathedral of 15° to locate the surface clear of the wing wake. Landing flaps are provided in the trailing edge of the wing to reduce the airplane attitude on landing and to provide a small increase in maximum lift.

The vertical tail is quite unique. The combination of high Mach number and angle of attack made the directional stability and control problem acute. For satisfactory directional stability, it was necessary to provide a ventral underneath the fuselage in addition to the upper vertical. The vertical tail surfaces were originally a 10-degree double wedge airfoil of 11% thickness, to achieve directional stability at small angles of yaw at highest flight Mach numbers Wind tunnel tests showed, however, that the aft portion of the diamond was not efficient in producing the required stability. Thus, the vertical tail sections were made into full 10-degree wedge sections. On both the upper and the lower surfaces the inner portion is fixed and the outer portion is moved as a unit by the rudder pedals, thus giving extremely effective directional control.

To provide satisfactory landing attitude, it is necessary to jettison the lower section of the ventral fin. This is done by explosive charges, triggered by landing gear extension, or by pilot switch. A parachute automatically opens and lowers this tail section to the ground, virtually undamaged. The inboard portions of the verticals are hinged at 60% element and are utilized as speed brakes, which are essential for speed control, and therefore, temperature control during re-entry.

The main landing gear is made up of two boat-shaped steel skids that are retracted close to the fuselage while in flight, and are extended by gravity and airloads. The skids are mounted on inflexible struts with an air-oil shock absorber attached to the upper end, which permits some outward rotation when the weight of the airplane is on the landing gear. The nose gear is a conventional, non-steerable, dual-wheel type, to provide directional stability on the ground. Neither main gear nor nose gear can be retracted by the pilot, only manually by ground personnel.

The canopy is a very minimum projection above the fuselage mold line but provides adequate over-the-nose visibility for the landing through the V-shaped windshield.

In accordance with our policy of providing good maintainability, numerous points of access to the equipment in the X-15 were designed into the structure (Fig. 9). This shows a good view of the tunnels on the side of the fuselage.

Although past research aircraft have been carried aloft partially submerged in the bomb bay of modified Air Force bombers, such as the B-29, it was decided to utilize the advantages of high-altitude, high-speed launch available with the B-52, and attach the X-15 under the right wing by a specially designed pylon (Fig. 10). This location required careful study of the aerodynamic interference factors and the launch path of the X-15. The location of the airplane on the wing of the B-52 meant that the pilot had to be in the cockpit before taxiing out, whereas in past research aircraft the pilot entered the test airplane from the bomb bay after reaching a specific altitude. The X-15 was located, therefore, in such a position that the pilot could use the ejection seat to clear the wing leading edge and all other obstructions, thus providing the

necessary safety in the event of trouble. Note the blister on the B-52 fuselage for viewing and photographing the X-15.

Many captive flights have been made where the B-52 landed with the X-15 still attached, with no problems encountered. In the event that the X-15 is fueled for a launch, and it is subsequently decided to return to base, all propellants are jettisoned overboard before landing (Fig. 11).

3. DESCRIPTION OF SYSTEMS

As mentioned before, the main fuselage of th X-15 is formed by the propellant tanks themselves (Fig. 12). The liquid-oxygen tank in the forward section is an annular-type tank with torus-shaped bulkheads and is separated into three compartments. This tank contains 1034 gallons of liquid-oxygen at -313°F at launch. In the center of the annular ring is a tank containing high-pressure gaseous helium. Other helium tanks, spherical in shape, are located throughout for use as source pressure, engine purge, control gas, and emergency jettison.

The ammonia tank combines an annular tank and a core tank containing a total of 1445 gallons. To the rear of the ammonia tank is a spherical tank for hydrogen peroxide, having a total capacity of 77.5 gallons. The tank incorporates a swivel-type pickup feed line that permits positive feeding regardless of airplane attitude. A combination vent pressure relief and tank pressurization valve is mounted on top of the tank. When the engines are not in operation, the system is vented to atmosphere, and when engine starting sequence is begun, the system is pressurized by helium gas, forcing the peroxide to gas generators which provide steam power for turbo-pump operation. There is also a jettison valve which permits the peroxide to be forcibly expelled overboard by the helium gas pressure. Just forward of the liquid-oxygen tank, we have located the auxiliary power units and the equipment bay which contains instrumentation.

A supply of liquid nitrogen for the cooling system is contained in one tank just forward of the liquid oxygen tank. Helium gas forces the liquid oxygen (Fig. 13) from the first compartment back into the second, into the third compartment, and out of the rear of the tank to the turbo-pump or the jettison line. The ammonia is forced from the rear and center compartments toward the forward compartment in a similar manner. Note the vent, pressure relief, and jettison provisions for each tank. The jettison tubes empty directly behind the tunnels at the side of the engine.

Since considerable liquid oxygen boils off during taxiing, climb, and cruise to the launch point, it is necessary to carry additional liquid oxygen in the B-52 mother airplane (Fig. 14). This tankage is used to top off the liquid-oxygen tanks in the X-15 just before launch. Two liquid-oxygen tanks are utilized, one called 'cruise tank' and the other called 'climb-out tank'. Again, spherical tanks of helium furnish gas to force the liquid oxygen into the X-15 under pressure. Float level valves in the X-15 automatically shut off supply when the tanks are full. One thousand gallons are contained in the cruise tank with 500 gallons in the climb tank. This is sufficient to provide a prelaunch cruise of about 2 hours.

Since the X-15 utilizes considerable hydraulic power and electrical power, even after the rocket engine ceases to operate, it was necessary to install auxiliary power units

(Fig. 15). To ensure complete safety, it was decided to install two power units side by side, driving independent hydraulic and electrical systems. Thus, a partial or complete failure of one power system does not prevent the airplane from continuing the flight. These units are manufactured by General Electric, are completely automatic, and employ constant-speed turbo-drive machinery. Fuel for each APU is provided by an independent feed system using helium pressure to move the monopropellant hydrogen peroxide. Each power unit is started and stopped by a switch in the cockpit and furnishes half of the electrical or hydraulic power required. Automatic shut-off for an overspeed condition is provided. After passing through a flow control valve, the hydrogen peroxide enters a decomposition chamber containing a catalyst bed made up of a series of silver and stainless steel screens which decompose the peroxide into superheated steam and free oxygen. This steam and oxygen mixture enters a nozzle box and drives the turbine. Nitrogen gas is introduced into the upper turbine bearing area for cooling.

To make sure that the peroxide will be fed out of the supply tank under zero or negative-g conditions, a collapsible bladder is used to line the tank. The helium pressure operates on the outside of the bladder forcing the peroxide out, regardless of gravity condition.

Two alternator-type generators furnish 400-cycle, 115-volt power to the primary busses. If one generator fails, the other generator automatically supplies power to both a.c. busses. Two transformer rectifiers are used to provide a 24-volt d.c. electrical system for other essential equipment.

The airplane contains two 3000 $lb/in.^2$ hydraulic systems, independent of each other, but operating simultaneously. Hydraulic systems supply power for operation of the flight control system, speed brakes, and wing flaps. Dual, tandem hydraulic actuators are used so that failure of one hydraulic system will still permit the other system to operate the various units.

Above the atmosphere, of course, there is no aerodynamic control and the body moves in a ballistic curve. However, the airplane must be properly orientated when the atmosphere is re-entered. To accomplish this orientation, we use the reaction jets in the nose for pitch and yaw and in the wing tips for roll control (Fig. 16).

The peroxide portion of the APU circuit is used to supply these reaction jets. Again, the peroxide under gas pressure is forced through catalyst beds and decomposed into steam and oxygen. There are six rockets in each of two independent systems, which normally operate simultaneously. One system includes four rockets in the nose for producing yaw and pitch, and two left-wing rockets. The other system contains the four remaining rockets in the nose and the two right-wing rockets for roll control.

The unique features of the X-15 cockpit are the ballistic control handle on the left console (Fig. 17) and the side stick aerodynamic control on the right console (Fig. 18). Movement of the ballistic control stick opens the metering valves, allowing peroxide to enter selected rockets. The motion of this control is such that a down motion of the control causes operation of the two rockets in the top of the nose section and pitches the airplane down. Yaw control is obtained by direct left or right movements of the stick, and roll control is obtained by simple wrist rotation. Stick force gradients are maintained for all three axes of operation by spring bungees.

The side console stick enables the pilot to easily control the airplane throughout the periods of high longitudinal and vertical accelerations when the weight of his hand might cause motion of the normal center stick. The right arm of the pilot is kept on the arm rest, and movements of the wrist are used for control. This side stick is coupled to the center stick linkage through pitch and roll hydraulic boost actuators to reduce stick forces and to synchronize displacements. The console stick also has a pitch trim knob and a microphone button.

The aerodynamic flight control system incorporates hydraulically actuated yaw, pitch, and roll control cylinders. The system is irreversible with artificial feel furnished by bungee springs.

The stability augmentation system provides damping inputs to the aerodynamic flight control system about all three axes. Major components of the system are a three-axis gyro, servo cylinders, and pilot-controlled gain selector switches. An interaction of the yaw and roll damping control circuits is provided, whereby signals from the yaw axis of the gyro are fed into the roll circuit to augment roll damping. This is appropriately referred to as the 'yar' control.

In addition to the normal flight instruments, the pilot's panel contains indicators for inertial attitude, velocity and height, which are driven from a gyro-stabilized platform. These are included to furnish the pilot necessary orientation information in his space environment when low air density makes conventional flight instruments inaccurate. The B-52 mother airplane has the necessary equipment to supply proper inertial conditions to a computer and thus align and stabilize the platform before launch. The system then dead-reckons from the launch point.

Cockpit air-conditioning and pressurization are furnished by a ram-air system used from take-off to pre-launch, or a liquid-nitrogen system used during X-15 flight (Fig. 19). The ram-air system does not pressurize the cockpit, but will furnish adequate cooling. The nitrogen system cools and pressurizes simultaneously. Helium gas is used to force the liquid nitrogen out of a segmented container and into a system of injectors where it becomes gaseous. Schematically, the gas is shown here as coming off the top of the tank. A mixing chamber and blower are used to continuously mix and recirculate the gaseous nitrogen. Thermostats are used to control the temperature by regulating the flow of nitrogen vapor.

The pilot's full pressure suit is ventilated and pressurized by gaseous nitrogen. If cockpit pressure should fail, the nitrogen supply will pressurize the suit to maintain 35,000 ft environment. The temperature of the gaseous flow to the suit may also be warmed by a small electrical heater. Wind-shield frost and fogging are eliminated by diverting some of this heated nitrogen gas to the area between the windshield glass panels, in addition to electrical heating of the inner glass.

Nitrogen gas also cools the APU bearings, pressurizes the hydraulic reservoir and inflates the canopy seal.

To reduce the cooling requirements of the temperature control system, fiber glass and aluminum foil are used as an insulation blanket around the cockpit area, thus maintaining inner wall temperatures at an acceptable level (Fig. 20).

The ejection seat was discussed by Mr. James Hegenwald of NAA at the May 1959 meeting in Athens, Greece. The subject will, therefore, be treated only briefly in this Report. It is dealt with more fully in AGARD Report 243.

We have used some old equipment in new ways. For example, a rocket-propelled seat that has all the comforts of home and hearth (Fig. 21).

The ejection seat (Fig. 22) permits safe pilot ejection up to Mach 4 in any attitude and at any altitude up to 120,000 ft. It has also been demonstrated to give satisfactory ejections at sea level as low as 90 knots airspeed. A ballistic rocket-type catapult supplies the ejection force, and stabilizing fins and booms automatically extend to stabilize the seat. Unlatching and raising either ejection handle on the seat fires the canopy remover, which, as it leaves the airplane, fires the seat catapult.

The pilot's parachute is carried in a container attached to the pilot's integrated harness with the pilot chute in a separate container.

The MC-2 full-pressure suit was modified for the X-15 airplane and has the restraining straps and parachute harness designed as an integral part of the suit (Fig. 23). A neck seal is used to keep the suit pressurization of nitrogen and breathing oxygen separated. The nitrogen flow through the suit also serves to cool the pilot's body. The oxygen regulator, suit pressure regulator, anti-g valve, and emergency oxygen supply are attached to the back of the restraining harness.

The suit itself consists of a number of integrated layers, each performing a specific function in the complete assembly. The first piece is a suit of light-weight cotton underwear. The function of this layer is to allow full circulation of ventilation air over the body and to provide for evaporation. The restraining layer is constructed of a unique distorted-angle material called 'link-net' by the manufacturer. The ballooning and elongating usually associated with an inflated pressure suit are controlled by this material. The 'link-net' material might best be described as a slipping torsion net which acts something like the old Chinese finger puzzle in that as it elongates, the circumference becomes smaller. As internal suit pressure increases, it tends to shorten the longitudinal dimension. Gloves and boots are attached to the restraining layer. The last layer to be donned, while not required for altitude protection, is an important part of the assembly. It contains an integrated parachute restraint harness, protects the pressure suit during routine use, serves as a sacrifice garment during high-altitude, high-speed bail-out and lastly, provides additional insulation.

The helmet consists of a fiber glass shell with a molded full head liner. All helmet oxygen and electrical services are internal within the helmet, and, therefore, are not affected by high-speed bail-out blast effects.

To perform its mission as a research vehicle, instrumentation must be installed as a standard system (Fig. 24). It was determined that the usual parameters would be supplemented by a thorough coverage of structural strains, temperatures, and deformation quite similar to the instrumentation coverage and techniques used in previous research aircraft by the N.A.S.A.

Approximately 100 strain gages were placed in the wing and tail sections, and about 800 temperature and pressure pick-ups were installed in the selected areas for reseach

and operational monitoring purposes (Fig. 25).

4. MATERIALS AND FABRICATION

One of the basic purposes of the X-15 flight program was to obtain experience at high levels of structural temperatures. In the re-entry condition at high speeds, portions of the airplane will reach temperatures as high as 1200°F (Fig. 26). As would be expected, the sharp leading edges of the fuselage, wings, and tail are heated to the highest temperatures. It is expected that the windshield bow in front of the pilot's face will glow cherry red, so that the cabin cooling system must do its job well.

To withstand these temperatures, it was necessary to use materials never before fabricated for aircraft (Fig. 27). Note that the leading edge is Inconel X and the web is titanium. The effect of internal radiation on peak temperatures is quite significant. A large portion of the fuselage and propulsion tank bulkheads is fabricated from Inconel, while the outside skin is formed of Inconel X, which is a heat-treated nickel alloy. The wing and tail surfaces are formed from Inconel X, and certain portions of the internal structure of the airplane, where temperatures are lower, are formed of titanium.

Forming of titanium presents problems with surface cracking, and it is necessary to anneal the part immediately after forming. Spinning was accomplished by heating the tools and part during the operation. Nicket alloys must also be annealed between successive forming operations. Many portions of the structure are welded using special fixtures. Both resistance and fusion welding are used (Fig. 28). All fusion welding was done before heat treatment, and, therefore, some elaborate fixtures were needed for control of contour during the heat-treating cycle. An important technique to control weight is material removal by a chemical etching process called 'Chem-Milling.' This process has been used extensively on the X-15 for both the nickel and titanium alloys.

5. SUBSTITUTION OF XLR11 ENGINE

Because of the delays in the development of the XLR99 engine, it was decided to proceed with the initial flights of the X-15 using two of the XLR11 engines (Fig. 29). These engines, with a total of 16,000 lb, are fitted neatly into the fuselage. They were adequate enough to begin initial testing of the airplane and its systems. Note the cutout in the B-52 flap for the X-15 tail. Quite satisfactory performance can be obtained, however, even with the limited thrust of these engines. A maximum Mach number of 3.3 and altitude of 136,500 ft have been attained, but not simultaneously (Fig. 30).

6. PILOT EVALUATIONS

Because of the nature of the flight above the atmosphere, in which the airplane is orientated by the ballistic controls, and the penetration of the atmosphere is accomplished at a fairly large angle of attack, it was considered desirable to do extensive work with flight simulation, to obtain a pilot evaluation of the cockpit presentation, and other sensory cues, under conditions of stress predicted for the new environments, and to give the pilots a thorough understanding of the operation and the possible problems (Fig. 31). Salient features of the panel presentation are the inertial height, inertial speed, angle

of attack, and source pressure gages. All other instruments are similar types.

A complete cockpit and control system were built up at N.A.A., and many hours were spent with an analog computer developing control feel and response characteristics, good re-entry characteristics, and in practicing the re-entry condition where the proper balance of load factor and heat rise must be achieved (Fig. 32). A steep angle of entry or low angle of attack entry means high temperatures and high recovery dynamic pressures, whereas a high angle of attack produces high load factors.

As another part of the pilot training program, extensive tests were performed in the Navy's centrifuge simulator at Johnstown, Pennsylvania (Figs. 33 and 34). Here it was possible, by use of the rotating capsule and analog computers, to permit the pilot to evaluate his cockpit controls and presentations under conditions close to those which will be experienced during actual re-entries. The acceleration effects were the best possible simulation and provided valuable information to the pilots as to what they could experience on future flights. Tests were made with various combinations of stability augmentation, and it was indicated that satisfactory entries could be made with those test conditions even if the dampers were inoperative.

With the high wing loading of the X-15 and low L/D ratio, it was to be expected that the sink rates during the descent and landing approach would be high (Fig. 35). When combined with the lack of engine power to adjust the sink rate, it was acknowledged that special evaluations of the landing approach conditions should be accomplished. To simulate the expected conditions of the X-15, it was decided to use an F-104 for pilot evaluation, since it was possible to obtain similar L/D characteristics by using flaps and speed brakes on the F-104 (Fig. 36). By performing landings at various reduced powers, it was possible to cautiously approach the landing conditions of the X-15. These power-off approaches from the F-104 were found to be a valuable tool in preparation for the X-15 landings, and, to date, all pilots have reported the X-15 landing characteristics to be very satisfactory using the techniques prescribed.

7. FLIGHT DEMONSTRATION

The first step on the road to the stars was to groom the vehicle for the exacting tasks of the research program. Our objectives in the initial flight tests were, therefore, to:

1. Check systems for proper functioning
2. Establish operational procedures
3. Check systems reliability
4. Check X-15/B-52 compatibility
5. Define launch characteristics
6. Make a limited check of stability, control, and structural integerity
7. Check landing characteristics.

The operational plan to achieve these objectives was established in three phases. The ground testing phase covered the powerplant test stand, the APU test stand, and, finally, the combined systems runs on the airplane (Fig. 37). The captive flight phase provided very valuable experience with systems operation and reliability at high altitude, cold temperatures, and dynamic environment. The stringent conditions of captive flight revealed problems that were not apparent during the ground tests. The ability to rehearse the procedures up to the moment of launch, and then recall the mission if anything malfunctioned or appeared doubtful, added a vast measure of safety and success to the program. The captive flights were restricted to the vicinity of the dry lake bed at Edwards Air Force Base to guard against the possibility that the X-15 would have to be jettisoned, because of some malfunction that might endanger the mother airplane, but would be satisfactory for an emergency glide landing (Fig. 38). The initial free-flight program was also restricted to gliding distance of the lake bed to allow safe landing in the event of powerplant failure. This resulted in a flight path that was seldom straight and, in fact, consisted mostly of turning conditions.

A typical test space positioning plot (Fig. 39) shows a straightaway run after launch, followed by one turn and a second straightaway, with the burnout occurring somewhere in the next turn at high altitude.

Planning of these flights must be carefully done, because of the limited time, which is about 4 minutes under power and another 5 to 6 minutes of glide.

Since there are essentially no stabilized flight conditions, all data must be obtained as transients and programmed in a sequence that will allow their accomplishment in a minimum time. Each flight, therefore, is planned with the use of an analog computer and is precisely timed to complete the data acquisition and yet keep the airplane within gliding distance of the primary lake bed at all times.

The compatibility of the X-15 with the mother ship was found to be excellent and the optimum launch condition is Mach 0.8 at 45,000 ft (Fig. 40). There is no interference at launch and the vehicle falls straight and true, with a moderate right roll. Light-up of the engine is quickly and smoothly accomplished and the airplane rotated to preplanned climb angle to reach the desired altitude and speed. After burn-out, the pilot performs additional tests during his descent and speed reduction until he reaches a point in the vicinity of the landing area. After this, he follows a standard pattern using an S turn that can be varied to adjust his position near the lake compatible with the altitude (Fig. 41). Final approach is made at a speed in the vicinity of 240 to 300 knots. At an altitude of about 500 ft above terrain, a 1.25g flare is initiated and held until touchdown, which occurs at speeds varying from 180 to 200 knots. The airplane is fully controllable at speeds down to 145 knots; however, these low speeds are avoided, because the angle of attack increases and creates a critical landing-gear load condition.

This is brought about by the far aft position of the main skids and the moment created by the c.g. acting about this contact point.

8. VALUE OF AN AIR LAUNCHING CAPABILITY

A few more remarks will be made on the value of an air launching capability, proven through the X-15 experience.

Past history has shown that the majority of problem areas and aborted flights occur during the initial test phases of any new development program. This, of course, is to be expected, since the space vehicle and its subsystems undergo, for the first time, a progression of build-up tests under increasingly more severe flight environmental and configuration loading conditions. The primary purpose of the initial series of flights is to determine whether problems exist and to define the problems sufficiently to allow resolution.

The method of air-launching research aircraft in the United States has been used since the first research airplane, the X-1. The prime purpose of using this method for the X-1 was to obtain the desired performance of the research aircraft. However, through the years of experience in the research airplane program, the advantages of being able to verify the proper functioning of the many propulsion and flight control systems, before the actual research aircraft flight, have resulted in an extremely high percentage of successful flights. For the X-15 research vehicle with many complex and unique systems pushing the state-of-the-art, the method of air launching is even more important in order to obtain the desired demonstration of the X-15 as a reliable airplane system. It is obvious, also, that during the conduct of the research program it will be possible to obtain the maximum flight data in the minimum amount of time and the minimum amount of flight attempts by using the air-launch technique.

The reliability of the X-15 in free flight has been exceptionally good, particularly when one considers that these are the initial flights on a new model. The high degree of free-flight success demonstrated by the X-15 does not imply that the X-15 was trouble-free, but also credits the inherent advantage of mission recall, in the event of malfunction during the captive portion of a launch test flight.

The X-15 has been carried aloft 39 times by the B-52 mother ship as of 1 September 1960. On 37 of these missions, the X-15 was scheduled to be dropped from the B-52 for a free powered flight or an unpowered glide flight. On 20 of these missions, successful drops were made, but 17 times the X-15 launch was aborted, because of malfunctions that showed up in captive flight during launch countdown with the B-52 serving as a first-stage booster. Only one serious malfunction occurred after X-15 launch, and this was a failure of the engine ignition, which could not be safely checked in captive flight. In this case, the X-15 was safely recovered by an emergency landing.

Typical of th problems encountered that required recall of the first stage booster were a liquid-ox en regulator malfunction, loss of command communications, and APU malfunctions.

The probability of mission success is greatly increased using an air launch rather than a ground-boosted launch. A more meaningful countdown is obtained in captive flight, because the airborne environmental aspects are more severe and more realistic than they are on the ground. It is believed that the low ambient temperature and pressure of captive flight may have contributed to some of the failures which were disclosed prior to launch. In fact, the systems checks during captive flight provide a continuous monitor of the operation to the point of first-stage separation. If any malfunction or irregularity occurs, the mission can be recalled. It is even possible to conduct certain trouble-shooting tests during the remainder of the same captive flight in an attempt to isolate causes of malfunctions. Conversely, in a ground-launched type of operation, separation of the X-15 from the first-stage booster would be committed as soon as the booster

was fired, regardless of any malfunctions that occur during first-stage flight.

The value of an air-launching capability for the unmanned missile was also demonstrated on the highly successful development program of the GAM-77 Hound Dog missile.

A mission success probability analysis for air launch versus ground-boosted launch has been made. We compared results that might have been attained if the 23 X-15 launch attempts accomplished as of 19 April 1960 had been ground-launched using ballistic missile boosters instead of air launched using a manned recoverable first-stage booster. The missile mission success probability figures used in the study were based on a flight-by-flight analysis of all major ballistic missile and space vehicle flights conducted in the United States. This included 256 flights in which ballistic missiles were expended.

Because of security reasons, only the X-15 details of this study can be discussed, but it can be stated that the entire study confirmed that an air-launched capability provides maximum effectiveness and flexibility per dollar and provides a greater mission success probability. The X-15 mission success probability was found to be 92.4% based on actual launches. If the X-15 had been launched on each captive flight, as would have been mandatory with a missile booster, the mission success probability would have been 56.6%. This is a direct measure of one advantage of the manned air-launch capability.

NAA has also conducted a study of the capabilities of a recoverable booster support system for launching payloads which require staging to achieve orbital conditions. A high-altitude, high-speed launch with a typical ICBM ballistic missile booster indicated at 260% increase in payload capability as compared to a ground launch. Main factors are less drag, a higher I_{sp}, and greater thrust for a constant fuel flow rate.

The significant advantages of the air-launching capability proven through actual experience are summarized as follows:

1. The first-stage booster is safely recovered after each flight, and is re-used for the entire flight test program;

2. Recall capability in the even of malfunction gives high probability of mission success;

3. Provides a continuous monitor of combined systems operation in the flight environment to the point of first-stage separation.

These result in maximum effectiveness and flexibility per dollar.

9. PROGRAM STATUS

1959 was a year of functional problems, reliability problems, and operational problems. A total of 15 captive flights were made and four free flights accomplished with the XLR11 engine. All of the systems were checked, improved, and re-checked. Operational procedures were rehearsed, modified, and polished.

In 1960, the careful preparation and improved reliability began to pay off. Twenty-four captive flights add 16 free flights were made in the first 8 months. One X-15 with

the XLR11 engine was delivered to NASA in January 1960, and rapid progress has been made in achieving their initial objective.

During August 1960, in the short space of one week, the X-15 established a new speed record of 2196 m.p.h. and a new altitude record of 136,500 ft. Already this remarkable machine has in its initial tests carried man higher and faster than he has ever been before.

The first airplane with an XLR99 engine will be delivered to NASA in December 1960, and the third and last vehicle is scheduled for delivery in 1961.

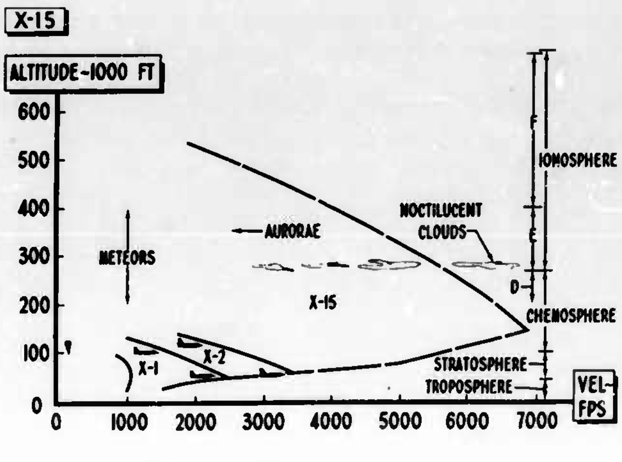


Fig. 1 Research in space

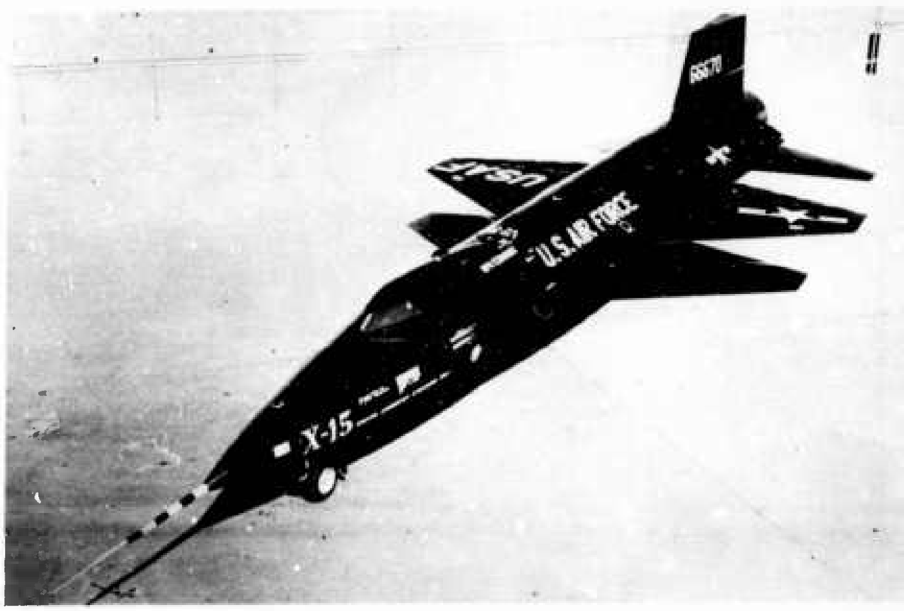


Fig. 2 Photograph of North American X-15

Maximum velocity, 6,600 ft/sec

Capability of attaining at least 250,000 ft

Representative primary structure to be capable of withstanding a temperature of 1200°F

Portions of representative structure should be able to achieve heating rates of 30 Btu/sq ft/sec

Purpose - to study problems of a manned space vehicle

Fig. 3 Design requirements for new research airplane

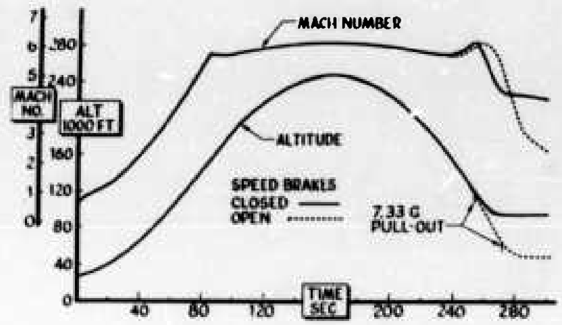


Fig.4 Design altitude mission

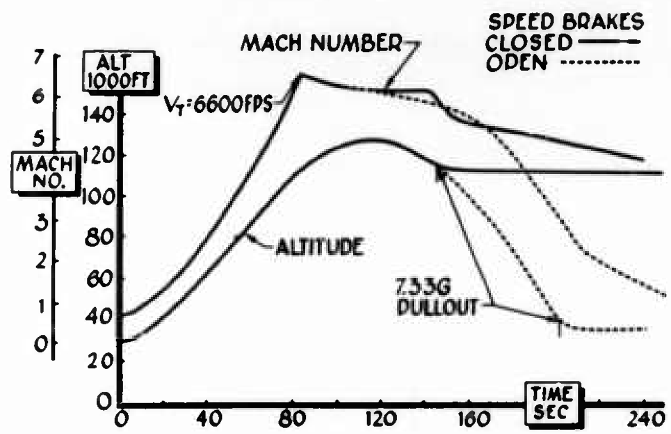


Fig.5 Design speed mission

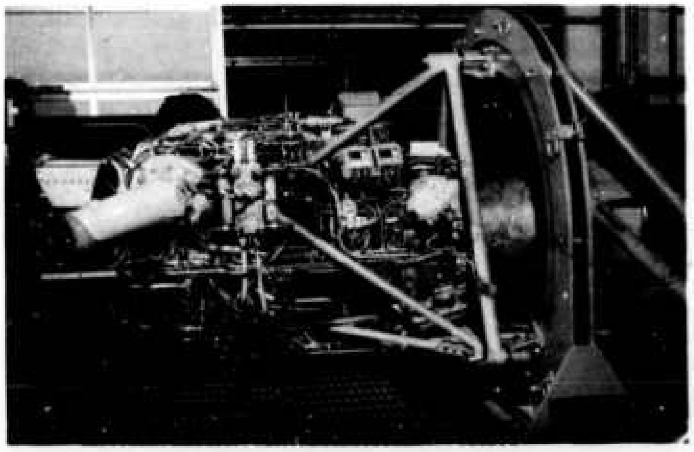


Fig.6 Reaction motors turbo-rocket engine XLR99

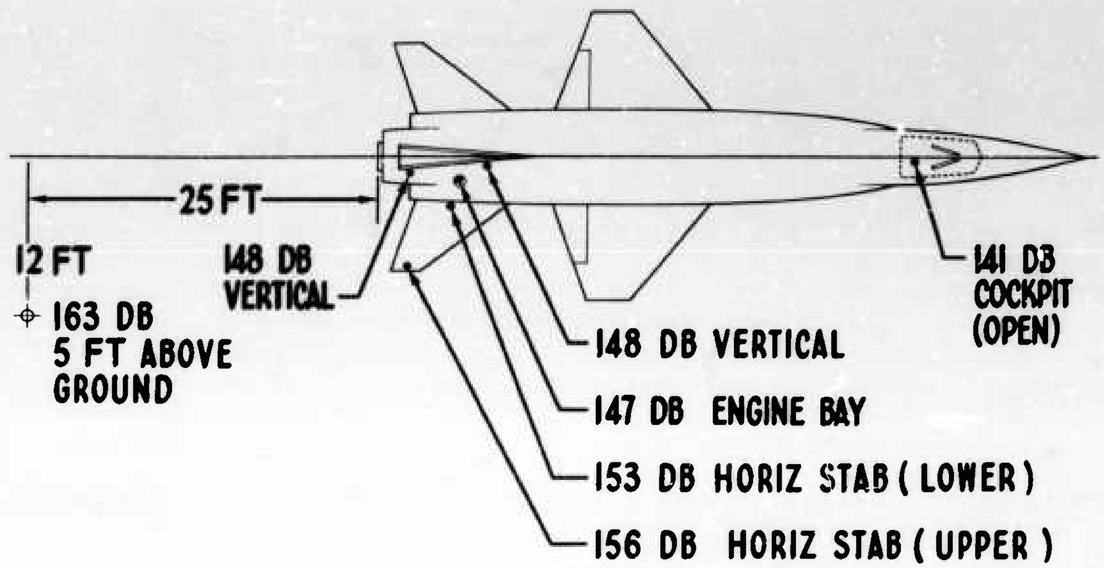


Fig.7 XLR-99 sound pressure levels (100% thrust)

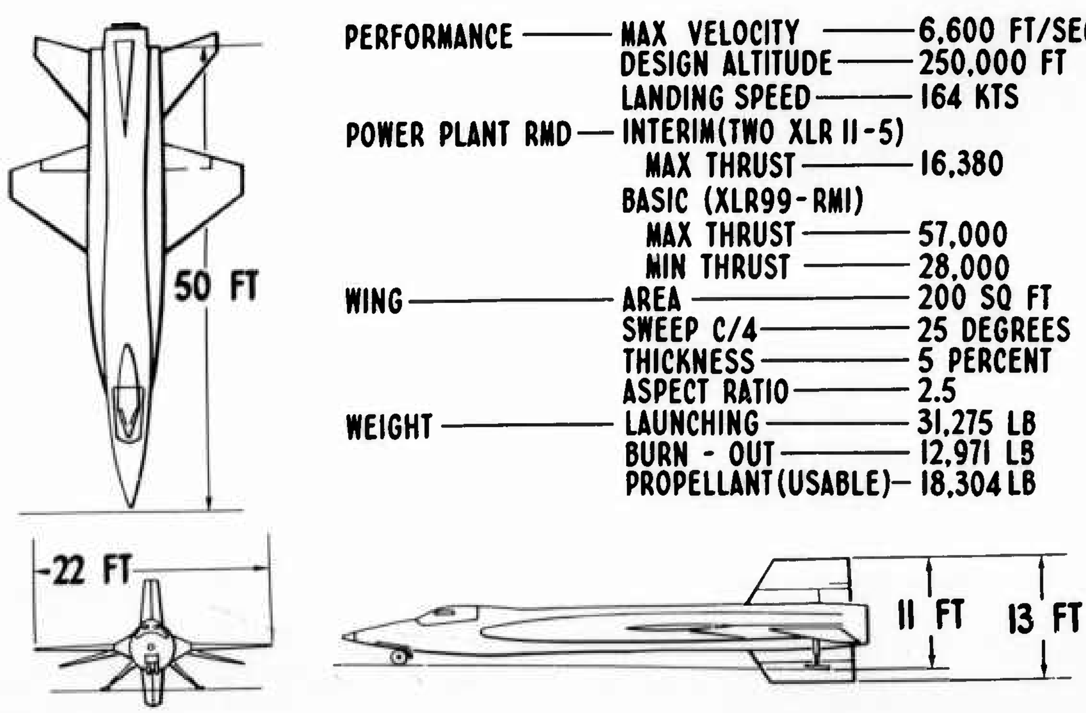


Fig. 8 Three-view layout of airplane to achieve desired performance

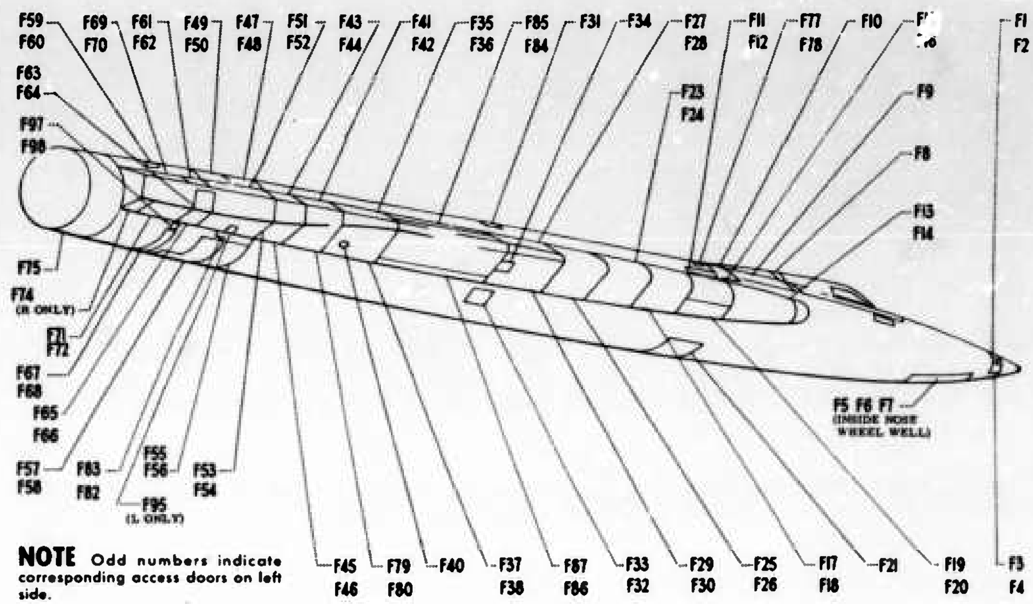


Fig. 9 X-15 access points

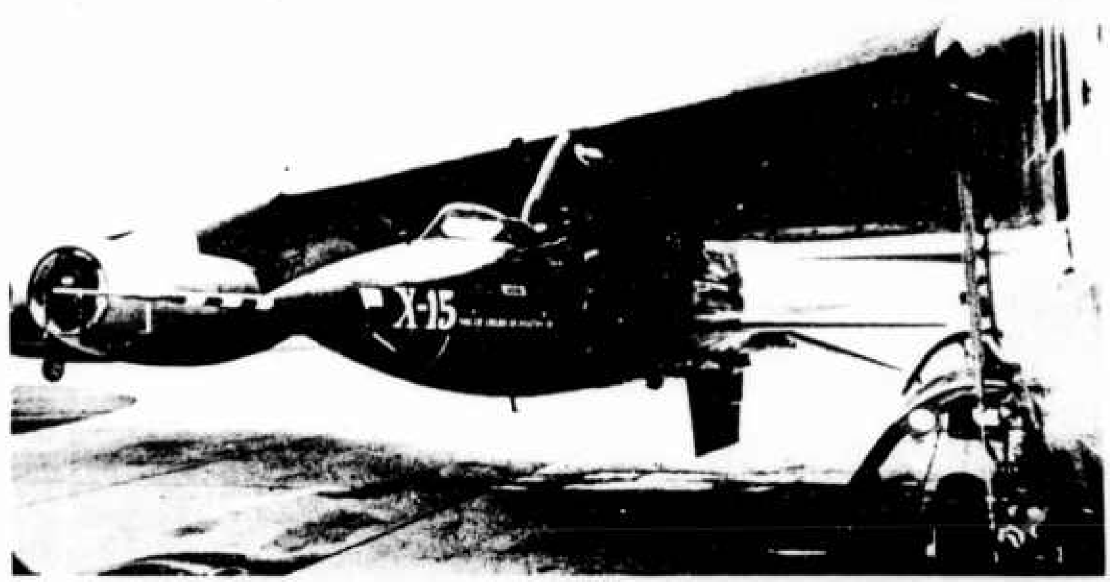


Fig. 10 Attachment of X-15 under wing of B-52

Fig. 11 X-15 airplane - general arrangement

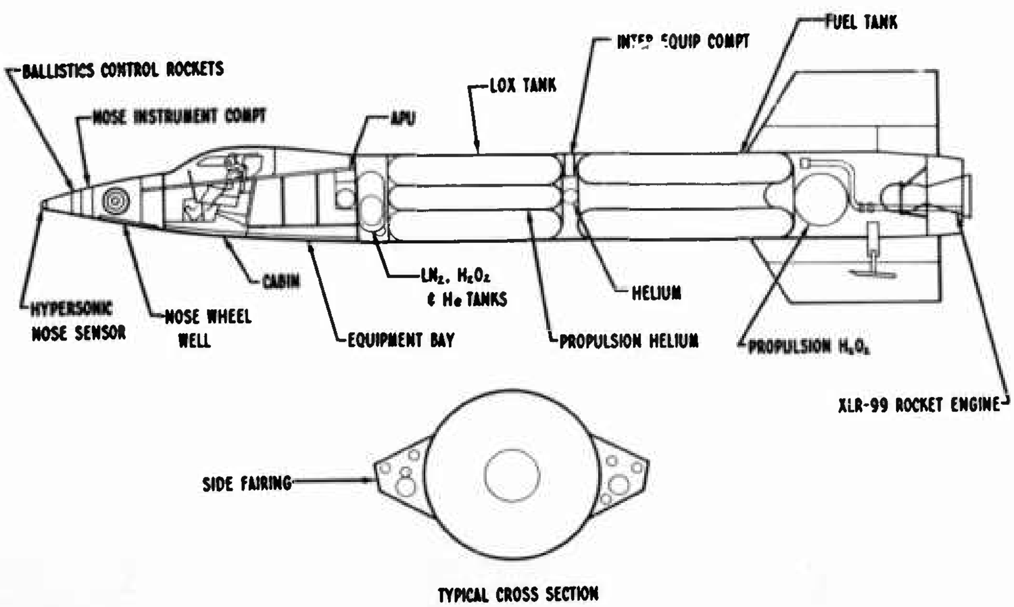


Fig. 12 Propellent tanks forming main fuselage of X-15

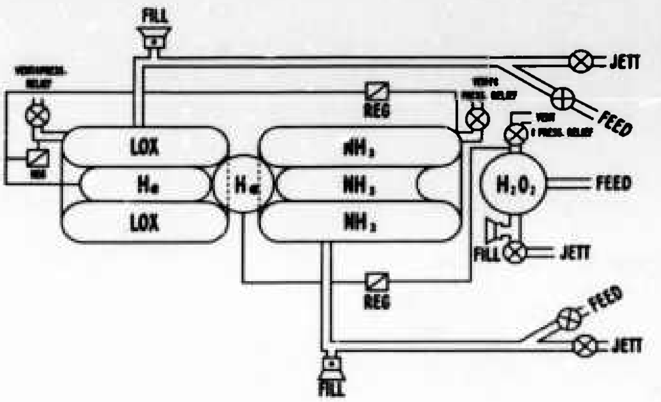


Fig. 13 Propellant supply system

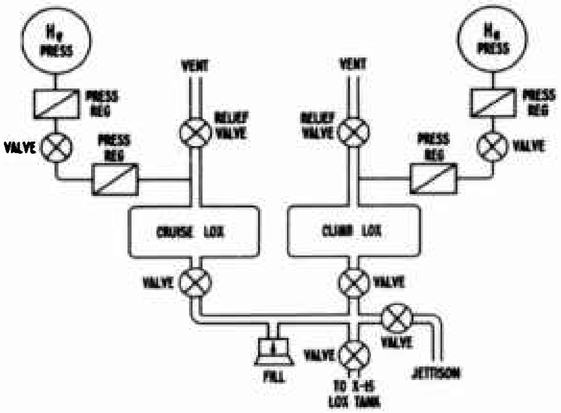


Fig. 14 B 52 LOX top-off system

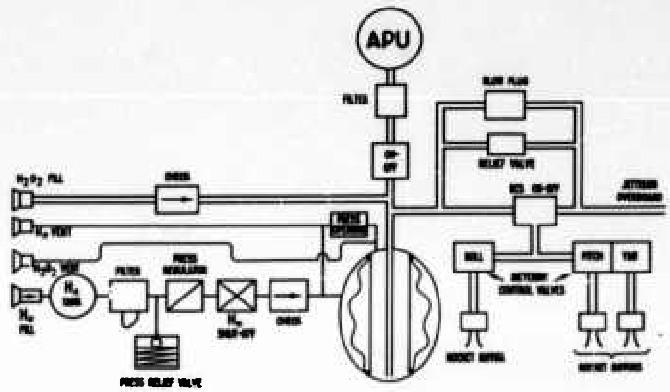


Fig. 15 APU and BCS feed system (H_2O_2 & He)

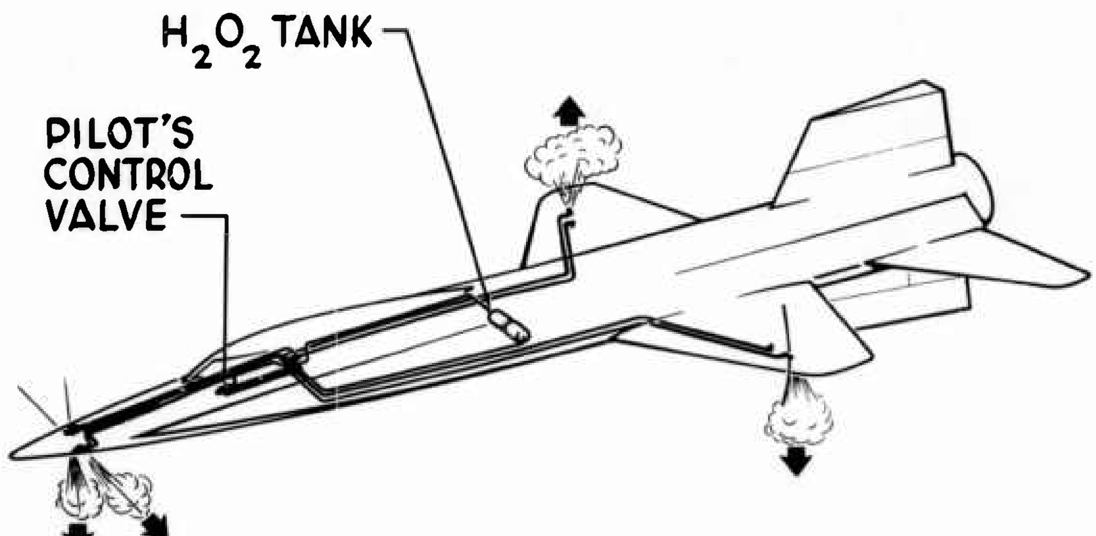


Fig. 16 Ballistic control

Fig. 17 Ballistic control handle (on left console)

Fig. 18 Side stick aerodynamic control (on right console)

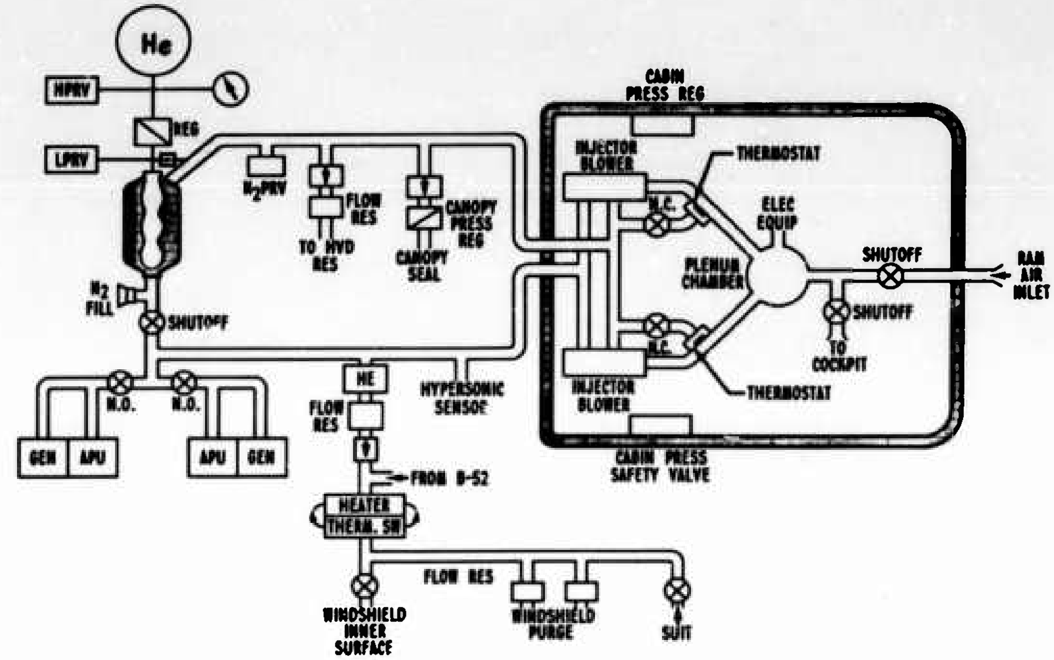
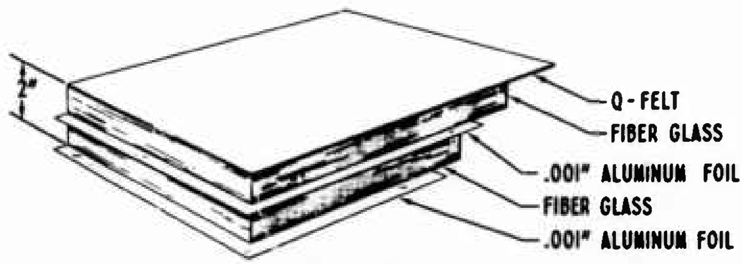


Fig. 19 Air conditioning and pressurization



$K_{EFFECTIVE}$ = 0.15 BTU/FT^2 HR - °F AT SEA LEVEL

- REDUCES COOLING REQUIREMENTS OF TEMPERATURE CONTROL SYSTEM
- MAINTAINS INNER WALL TEMPERATURE TO ACCEPTABLE LEVEL

Fig. 20 Insulation blanket

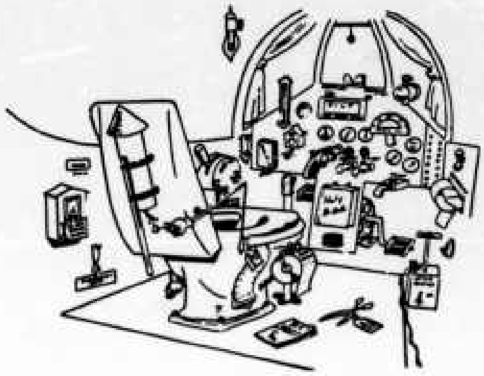


Fig. 21 New uses for old equipment

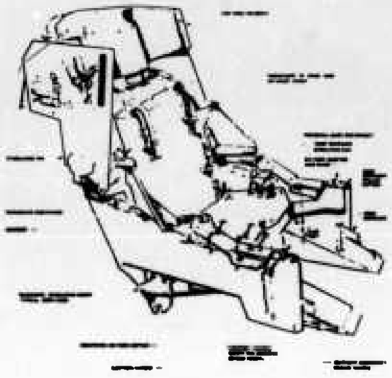


Fig. 22 X-15 ejection seat

Fig. 23 Modified MC-2 full-pressure suit

ACCELERATIONS

ATTITUDE ANGLES

ANGULAR VELOCITIES

CONTROL POSITIONS & FORCES

ENGINE PRESSURES AND TEMPERATURES

STRUCTURAL STRAINS, TEMPERATURES AND DEFORMATIONS

SURFACE PRESSURE ORIFICES

VELOCITY

ALTITUDE

AIR TEMPERATURE

MACH NUMBER

AIR FLOW ANGLES

Fig. 24 Measurements required for X-15

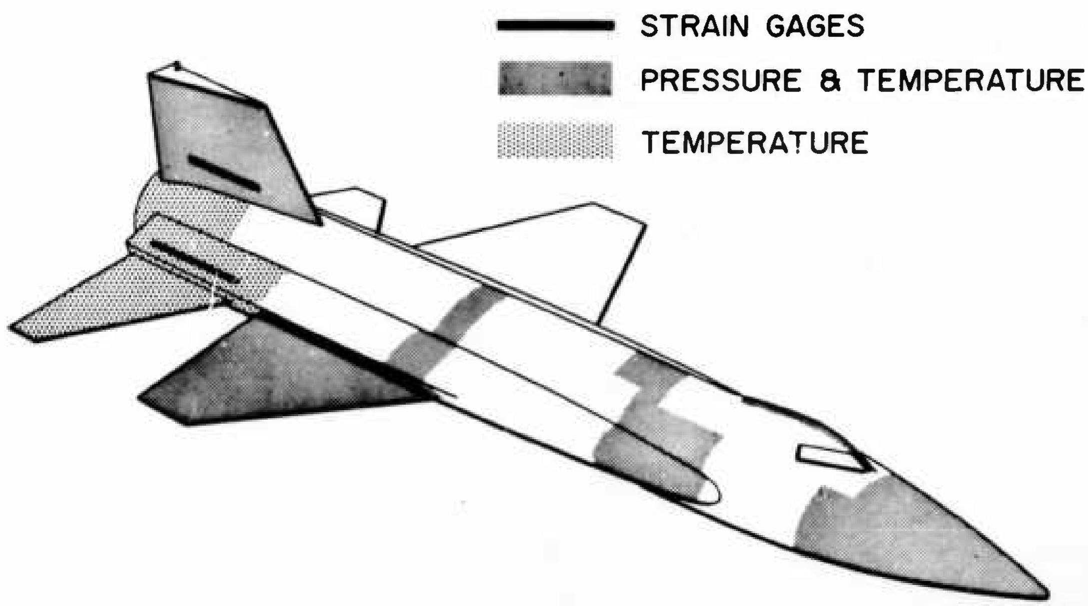


Fig. 25 Research instrumentation

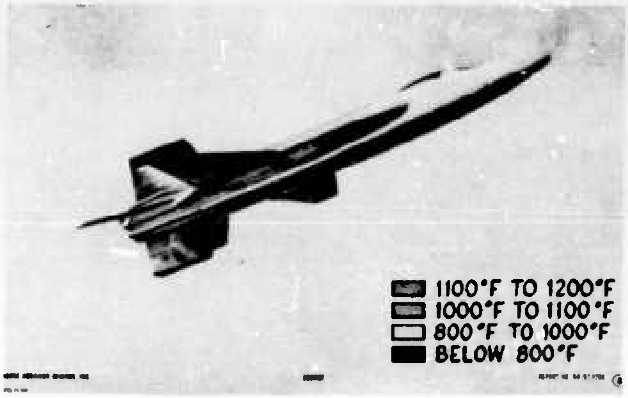


Fig. 26   X-15 aerodynamic heating

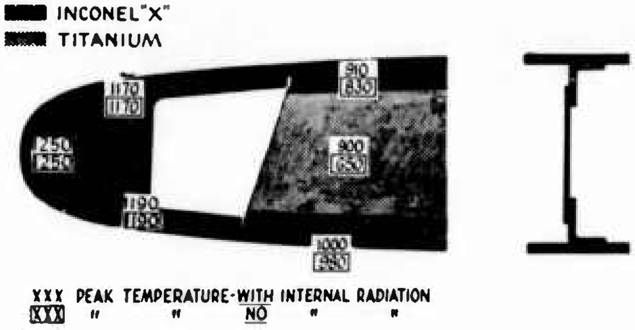


Fig. 27   Effect of internal radiation on leading-edge-structure temperatures (speed mission)

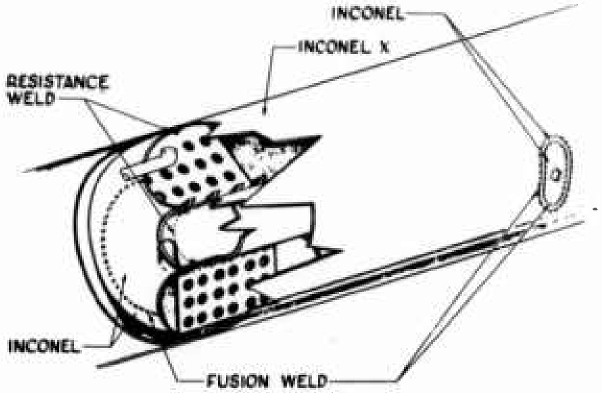


Fig. 28   Fuselage construction

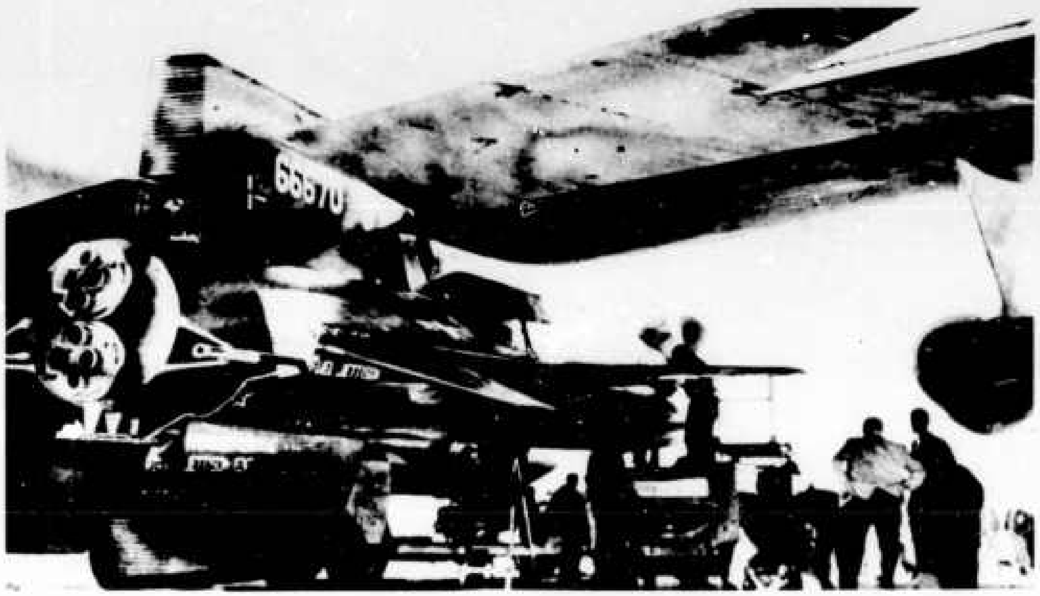


Fig.29   XLR-11 engine installation

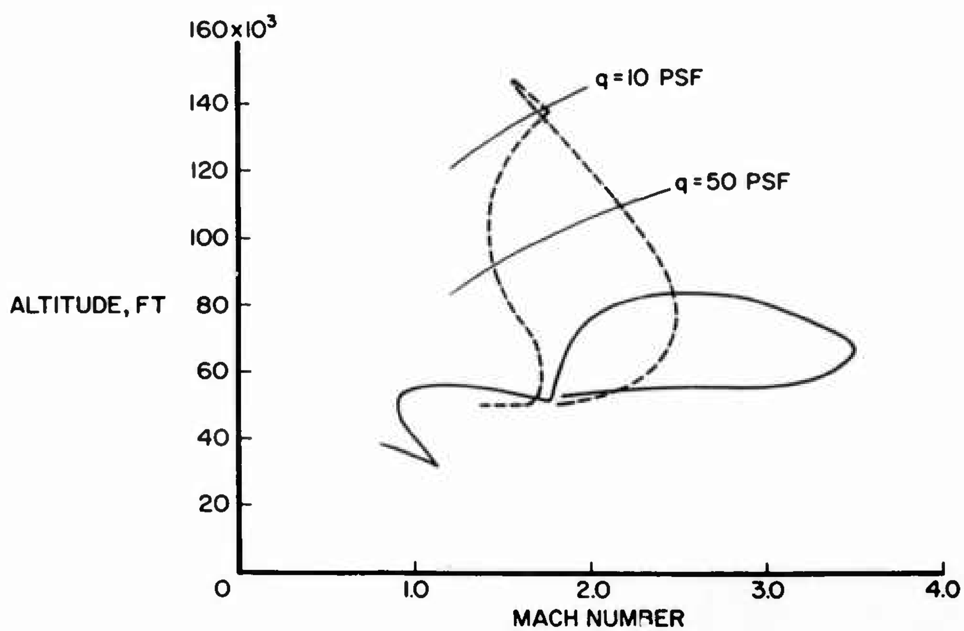


Fig.30   X-15 research program (LR-11 engine)

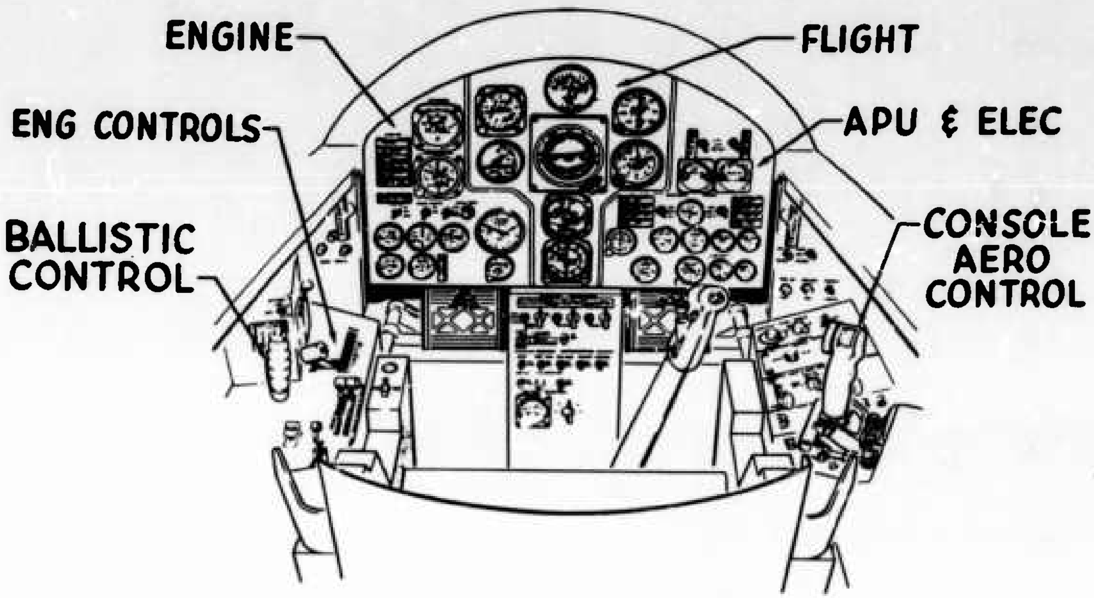


Fig.31 X-15 cockpit

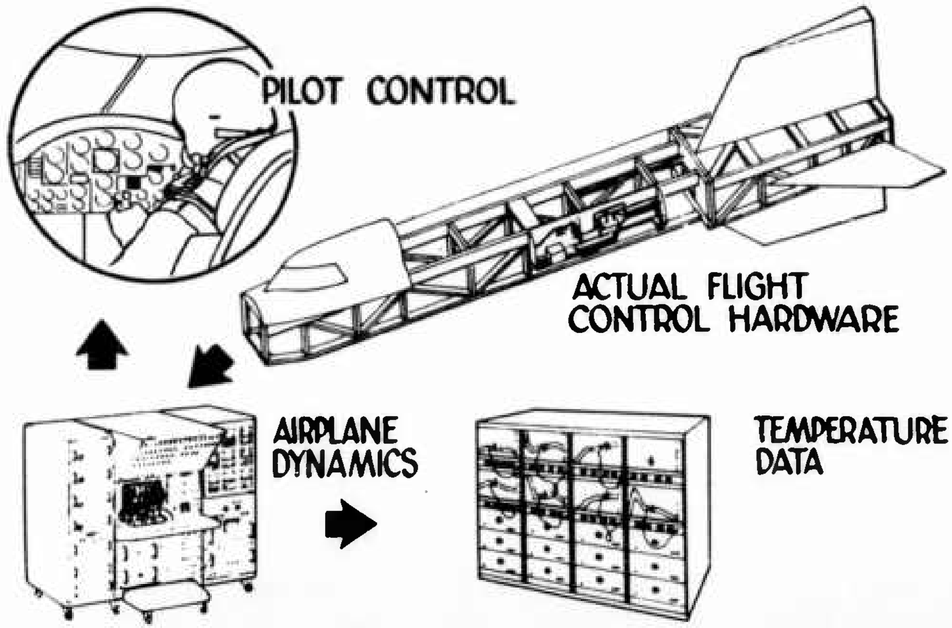


Fig.32 Flight simulation

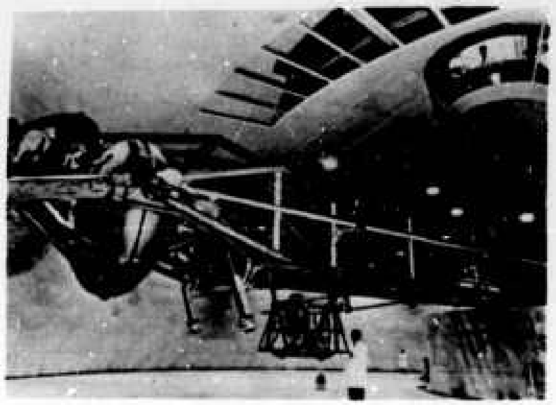


Fig.33 Navy centrifuge simulator, Johnstown

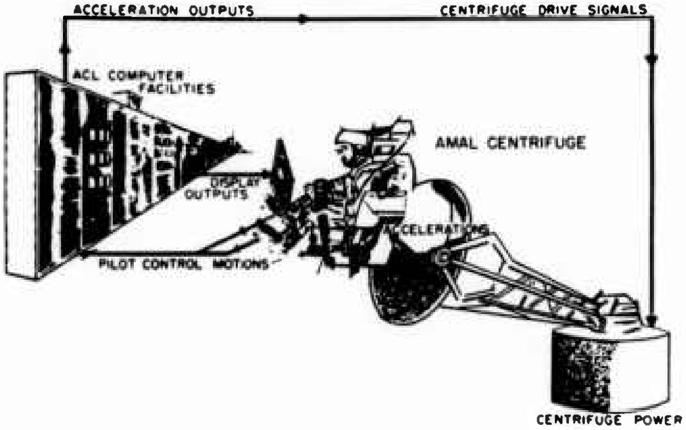


Fig.34 Navy centrifuge simulator, Johnstown

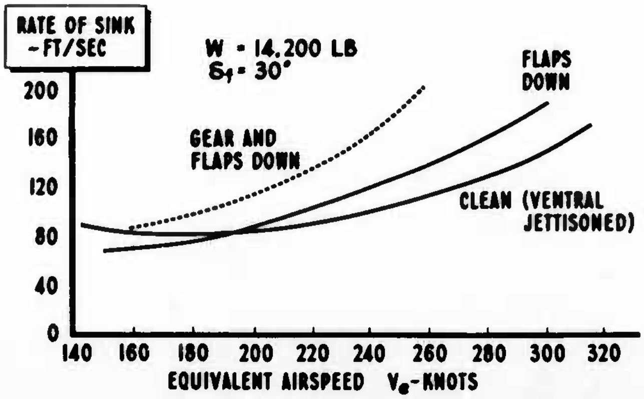


Fig.35 Rate-of-descent characteristics

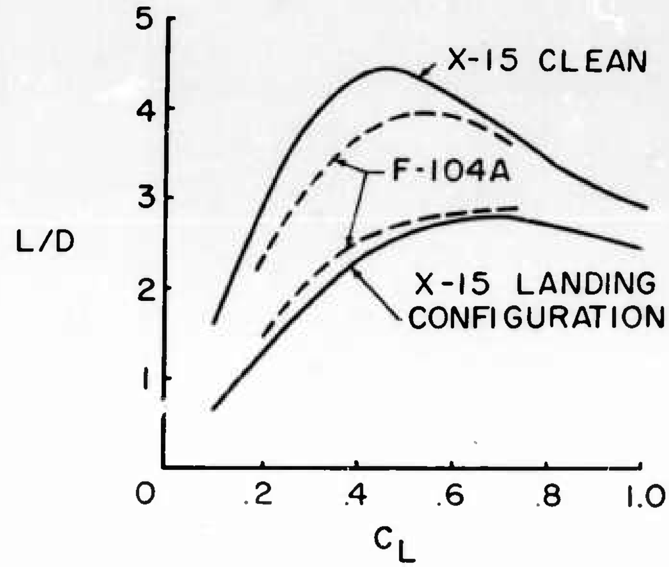


Fig.36 Comparison of L/D obtained in F-104A landing tests with X-15

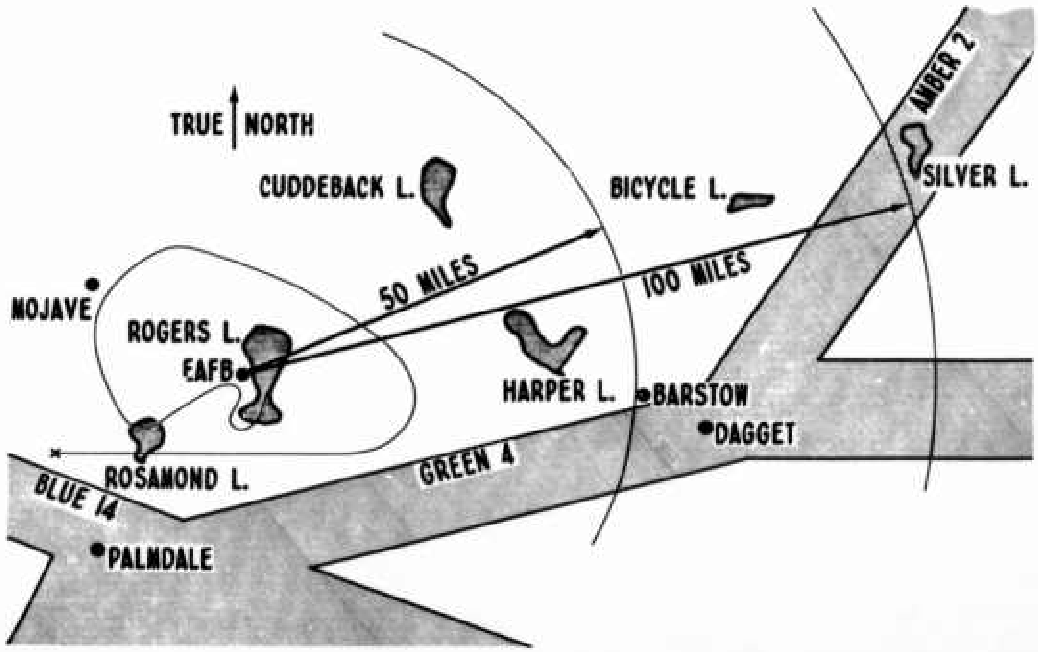


Fig.37 Edwards flight test area

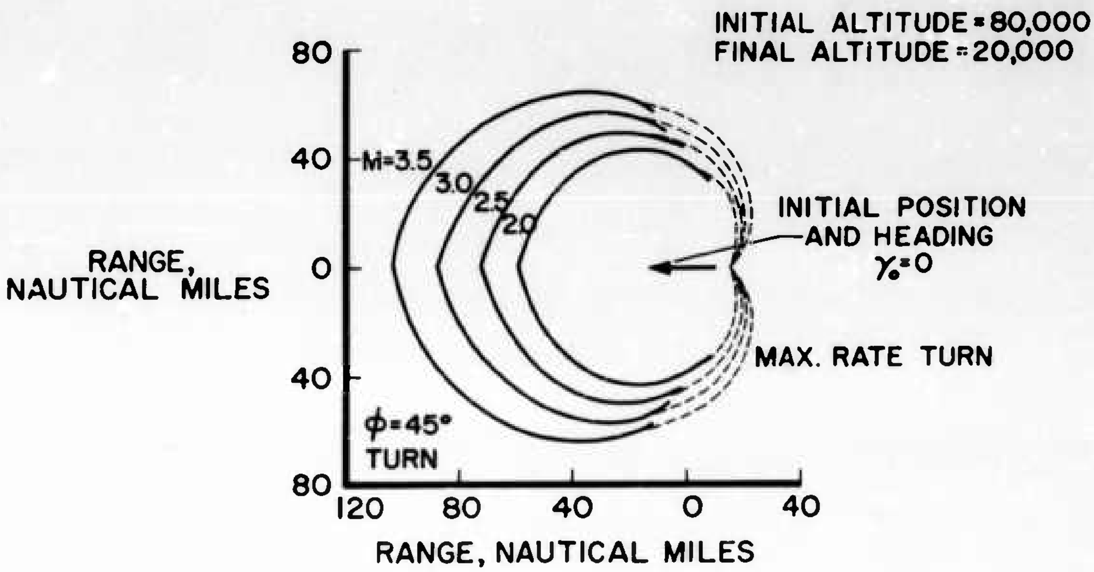


Fig. 38 X-15 range during gliding flight

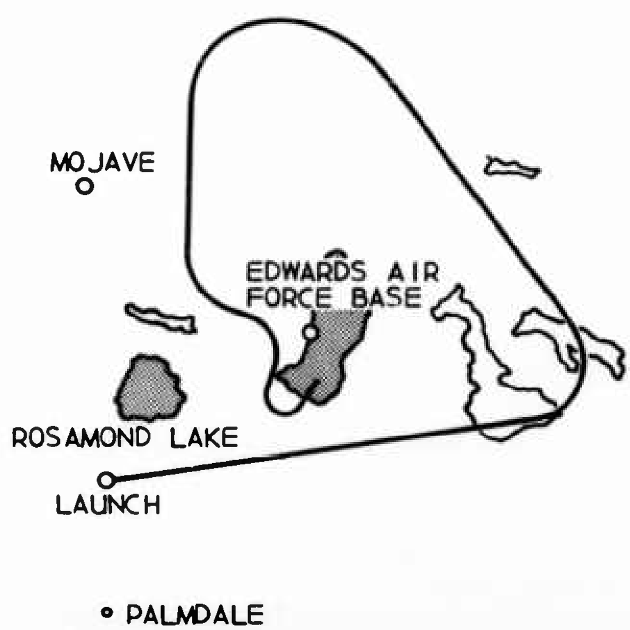


Fig. 39 Typical test mission space positioning

Fig.40 X-15 launch from mother ship

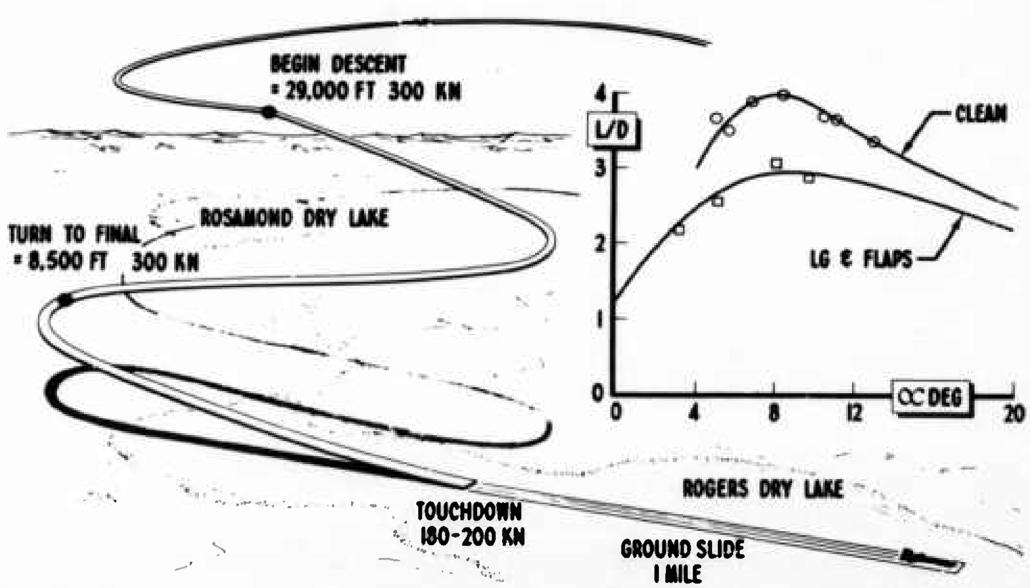


Fig.41 Landing characteristics flight test data

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DESIGN AND OPERATION OF THE X-15 HYPERSONIC RESEARCH AIRPLANE
1960
31 pages incl. 41 figs.

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This Report was presented at the Flight Mechanics Panel held from 3-5th October, 1960, in Istanbul, Turkey

629.135.072.2
533.6.011.55
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